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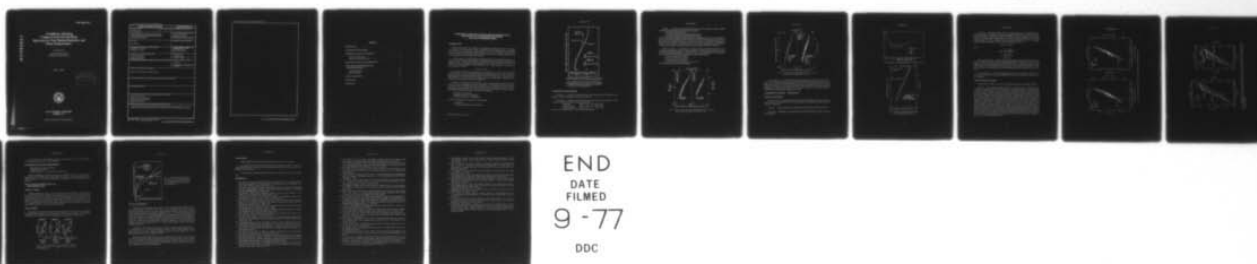   JUN 77   A M SULLIVAN
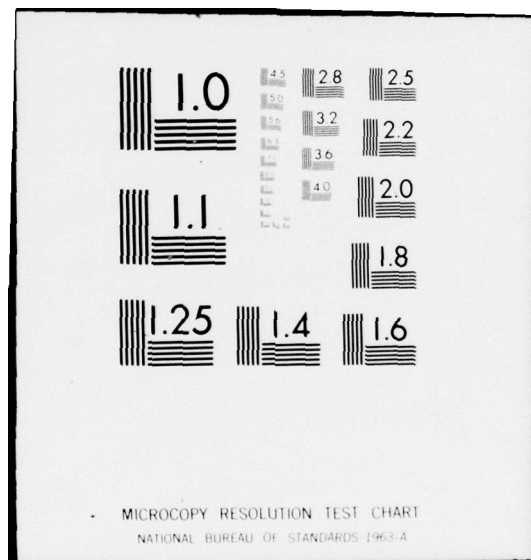
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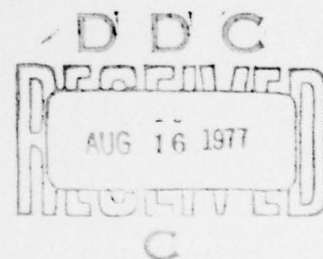
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Conditions Affecting Fatigue-Crack-Growth Rate: Relevance to Test Method Selection and Data Interpretation

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Strength of Metals Branch
Engineering Materials Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The literature of fatigue and corrosion fatigue crack-growth rate contains many discrepancies. The many variables associated with fatigue crack-growth rate are classified, and their relative significance is discussed.

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CONTENTS

CONDITIONS AFFECTING FATIGUE-CRACK-GROWTH RATE: RELEVANCE TO TEST METHOD SELECTION AND DATA INTERPRETATION

INTRODUCTION

Fatigue-crack-growth rate (FCGR) is of fundamental importance to structural integrity technology. The material of any structure subjected to repeated loading cycles is a candidate for the initiation and propagation of fatigue cracks. Since it is now generally recognized that virtually all structures will contain cracks or imperfections that can be considered cracklike defects, propagation will be the stage discussed here.

FCGR testing has a long but often unrecognized history. Crack-growth information was buried in "cycles-to-failure" fatigue data for many decades and was not specifically identified for engineering use. No adequate engineering representation existed until 1963, when Paris [1] showed that FCGR expressed as da/dN appeared to be a unique function of stress-intensity factor range ΔK, such that

$$da/dN = A\,\Delta K^n. \tag{1}$$

An extensive amount of data has since been collected and analyzed in this fracture mechanics format. Later, it became obvious that the log-log plots of Eq. (1) were actually sigmoidal, the linear approximation being valid only over the midrange (Fig. 1). Because this midrange generally coincides with service loading conditions, representation of FCGR by this simple Paris law remains of great practical importance.

However, even the most casual literature survey reveals glaring discrepancies between results of various investigations and their interpretation. It is well known that many factors can influence the crack-growth resistance of materials; these naturally enter into the design of laboratory tests for such properties. An attempt to classify some important variables associated with FCGR testing seems warranted. These will be discussed as

Conditions of the material
Conditions of the test —mechanical
Conditions of the test —environmental

and will be considered with respect to two environments:

1. Ambient air
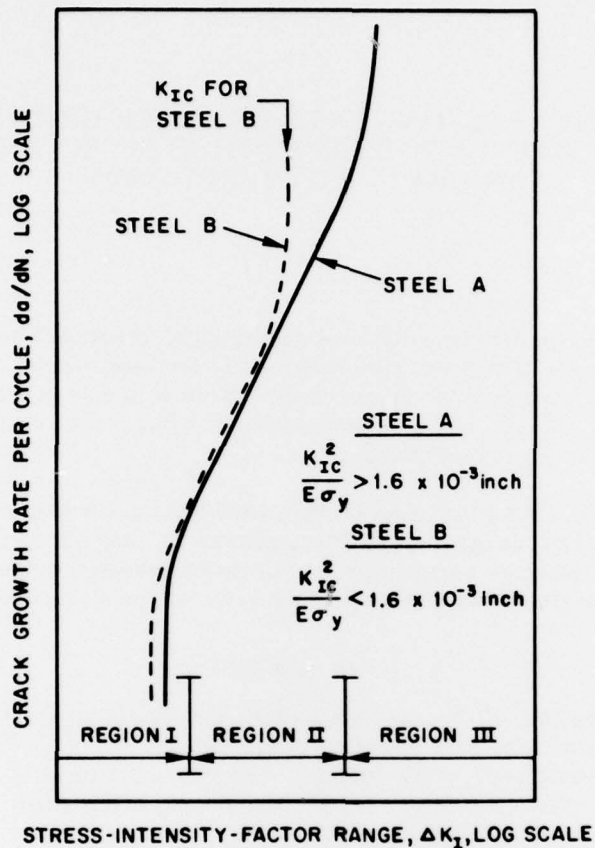2. Aqueous and saline (3.5 percent NaCl)

1

Fig. 1 — Schematic of $da/dN = A\Delta K^n$ as log da/dN vs log ΔK, showing sigmoidal nature of curve with linearity only in Region II. (Reprinted, with permission, from Ref. 2, p. 193. © 1973 American Society for Testing and Materials.)

CONDITIONS OF THE MATERIAL

Alloy System — Variations in the alloy system (steel, aluminum, and titanium) seem to influence somewhat the value of the exponent in Eq. (1).

Microstructure — Different values of the preexponential constant and exponent n in Eq. (1) may be characteristic of certain steel microstructures:

Martensitic: $da/dN = 6.6 \times 10^{-9}\Delta K^{2.25}$ [3,4]
Ferritic-Pearlitic: $da/dN = 0.36 \times 10^{-9}\Delta K^{3.00}$ [3]
Austenic Stainless: $da/dN = 0.30 \times 10^{-9}\Delta K^{3.25}$ [5-7].

Deviations from these numerical values will be discussed later.

2

Thickness — Ambiguity and inconsistency characterize the literature of thickness effects on FCGR, since three types of response are documented:

1. No effect of thickness [8-11]
2. Growth accelerated by increased thickness [4,12]
3. Growth accelerated by decreased thickness [13,14].

Tests at NRL showed a slight increase in FCGR and considerable scatter in tests on specimens cut from an as-heat-treated plate of 5Ni-Cr-Mo-V steel. When this material was stress relieved after being cut, no effect of thickness was noted but FCGR was substantially increased [15] (Fig. 2). Further studies on A516-60 steel from a series of test specimens of varied thickness normalized, cut down, and stress relieved, again show *no effect of thickness* [16] (Fig. 3).

Processing History — The discussion of specimen thickness effects demonstrates that specimen processing affects FCGR. Lack of uniformity in such processing, together with a lack of reported processing information, is believed to have contributed largely to the ambiguities cited in this report. Sequences of processing can be described as follows:

1. Roll to size, heat treat, and test
2. Cut to size, heat treat, and test
3. Heat treat, cut to size, and test
4. Stress relieve prior to testing in (1), (2), or (3).

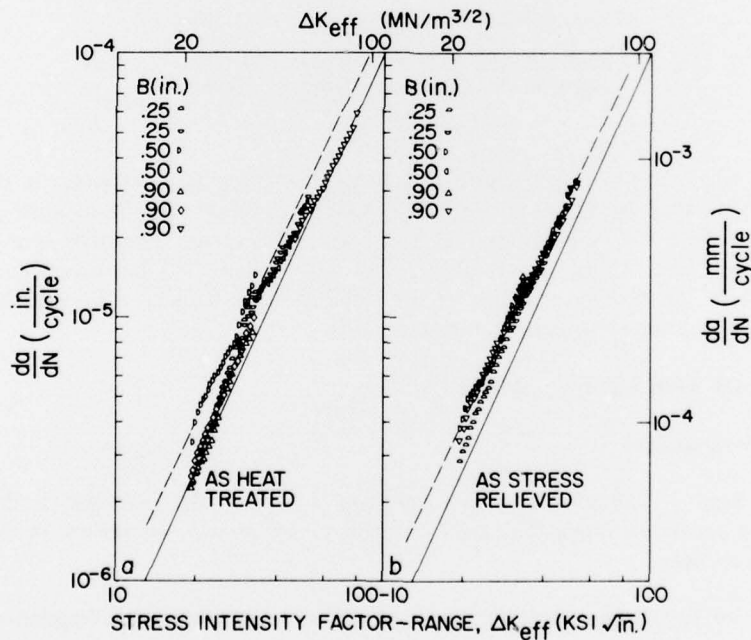All of these require experimental investigation.

Fig. 2 — *da/dN* vs Δ*K* for 5Ni-Cr-Mo-V steel: effect of thickness in specimens tested as heat treated and stress relieved (Ref. 15, Fig. 2)
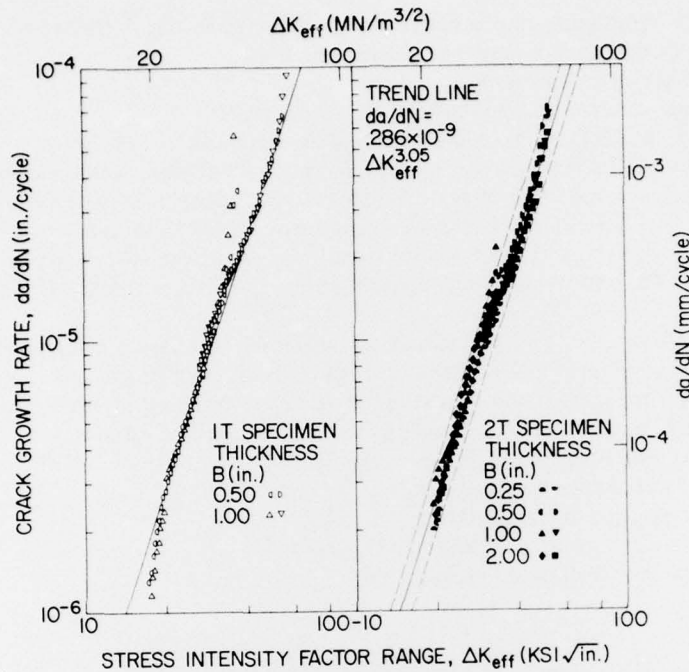
Fig. 3 — da/dN vs ΔK for A516-60 steel: effect of thickness in 1-T and
2-T WOL-type CT specimens (Ref. 16, Fig. 2c)

Yield Strength Level — Limited information on the effect of yield stress is available. Fatigue tests on 4340 steel tempered at a series of different temperatures show ambiguous results. Both Anctil and Kula [17] and Miller [18] find a variation in the exponent n of Eq. (1) with tempering temperature. On the other hand, Imhof and Barsom [19] find no effect of tempering temperature. A replot of these data can be seen in Fig. 4. Studies on a 17-4 stainless steel indicate little effect of tempering temperature on n [19].

CONDITIONS OF THE TEST — MECHANICAL

Ambient Air Environment

Specimen Type — The specimen type does not appear to affect the test results. In Fig. 5, data from three specimen types (CT, CCT, and SEN) are shown together with the trend line from the CT specimen.

Frequency — Tests in ambient air are apparently not affected by test frequency [20,21].

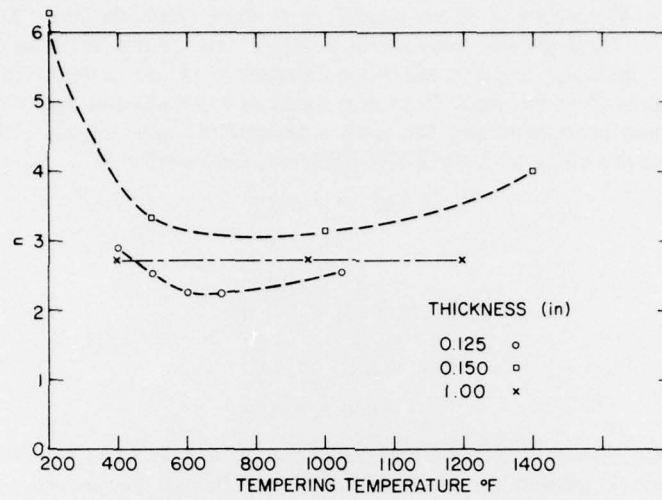*Waveform* — No difference in test results were noted with sinusoidal, triangular, or square waveforms [20].

4

Fig. 4 — Exponent *n* vs tempering temperature for 4340 steel [17, 18]
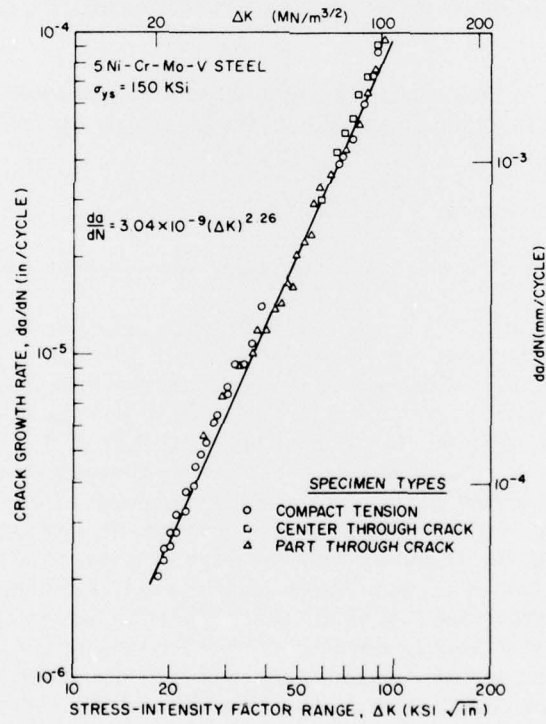

Fig. 5 — Results of tests from three specimen types:
CT, CCT, and SEN (Ref. 15, Fig. 3).

5

Stress Ratio — The effect of stress ratio R is evident (Figs. 6a, 6b). At present the apparent acceleration of crack-growth rate cannot be explained. However, development of a generalized relationship incorporating the effects of different R values is important; it would allow estimates of crack growth to be made from one series of experimental determinations. Several complex models have been proposed for such a generalized relationship [23-27]. A simpler model [22] describes the effect of R for a 5Ni-Cr-Mo-V steel such that

$$da/dN = A \, \Delta K_{eff}^n$$

where

$$\Delta K_{eff} = \left(\frac{1 - bR}{1 - R} \right) \Delta K$$

$$b = 0.85, \, R \geqslant 0$$

$$= 1.40, \, R \leqslant 0.$$

Stress Amplitude History — Recent literature reports both acceleration [28] and retardation [29,30] of fatigue-crack growth due to load sequence effects. To predict the latter, several models have been proposed [30-33]. One attempt to normalize da/dN from variable-amplitude loading studies uses a root-mean-square (rms) value of $\Delta \sigma$ for computing ΔK [34]. An equally successful effort at normalization of ten block loading profiles uses the simple mean value only [35].

Service Conditions — From the foregoing discussion of test conditions in ambient air, it can be seen that only stress ratio and amplitude (variable) have an immediate bearing on service conditions.

Aqueous and Saline Environment

Specimen Type — There is no evidence to suggest that specimen type influences FCGR.

Frequency — This variable is highly important when testing is done in an aggressive environment. In general, the lower the frequency the more pronounced the increase in FCGR expressed as da/dN. Actually, of course, the time of crack growth to failure is greatly increased at lower frequencies. Good coverage of the effect of frequency has been made on X-65 line pipe steel by Vosikovsky [21], on HY-80 and 4340 by Gallagher [36], and on 4340 by Krafft [37]. Data from Ref. 21 cover approximately four orders of magnitude of da/dN and were obtained under conditions of free corrosion and cathodic potential. Three regions of growth are identified. Available data for a condition of free corrosion are seen in Fig. 7a and those for cathodic potential in Fig. 7b. Departure from the slope of Region I at higher values of da/dN as the frequency is reduced is evident. Also evident is the fact that the slope of Region I is higher in the NaCl environment than in air. Other results by Barsom concerning the effect of frequency confirm that it is more pronounced at lower frequencies [19,38]. What is surprising about these data, however, is that the authors are apparently discussing Region II environmental data and find no slope change from air data, (Figs. 8a, and 8b). Crooker and Lange [39], on the other hand, testing at higher values of da/dN and ΔK, show data obviously belonging to Region II in a 12Ni maraging steel (Fig. 9).

6

SPECIMEN
PTC
R = 0   ○ □
R = -1   ◆
R = -2   ▲ ▼

R VALUES (-)
-2
-1
0

ΔK (MN/m3/2)

ΔK (KSI √IN.)

STRESS INTENSITY FACTOR RANGE, ΔK (KSI √IN.)

da/dN (in./CYCLE)

da/dN (mm/CYCLE)

(b) R values ≤ 0 (Fig. 4b)

SPECIMEN
PTC
R = 0   ○ □
R = 0.50   △ ▽
R = 0.67   ▷
R = 0.75   ◁

R VALUES (+)
0.75
0.67
0.50
0

ΔK (MN/m3/2)

STRESS INTENSITY FACTOR RANGE, ΔK (KSI √IN.)

da/dN (in./CYCLE)

da/dN (mm/CYCLE)

(a) R values ≥ 0 (Fig. 4a)
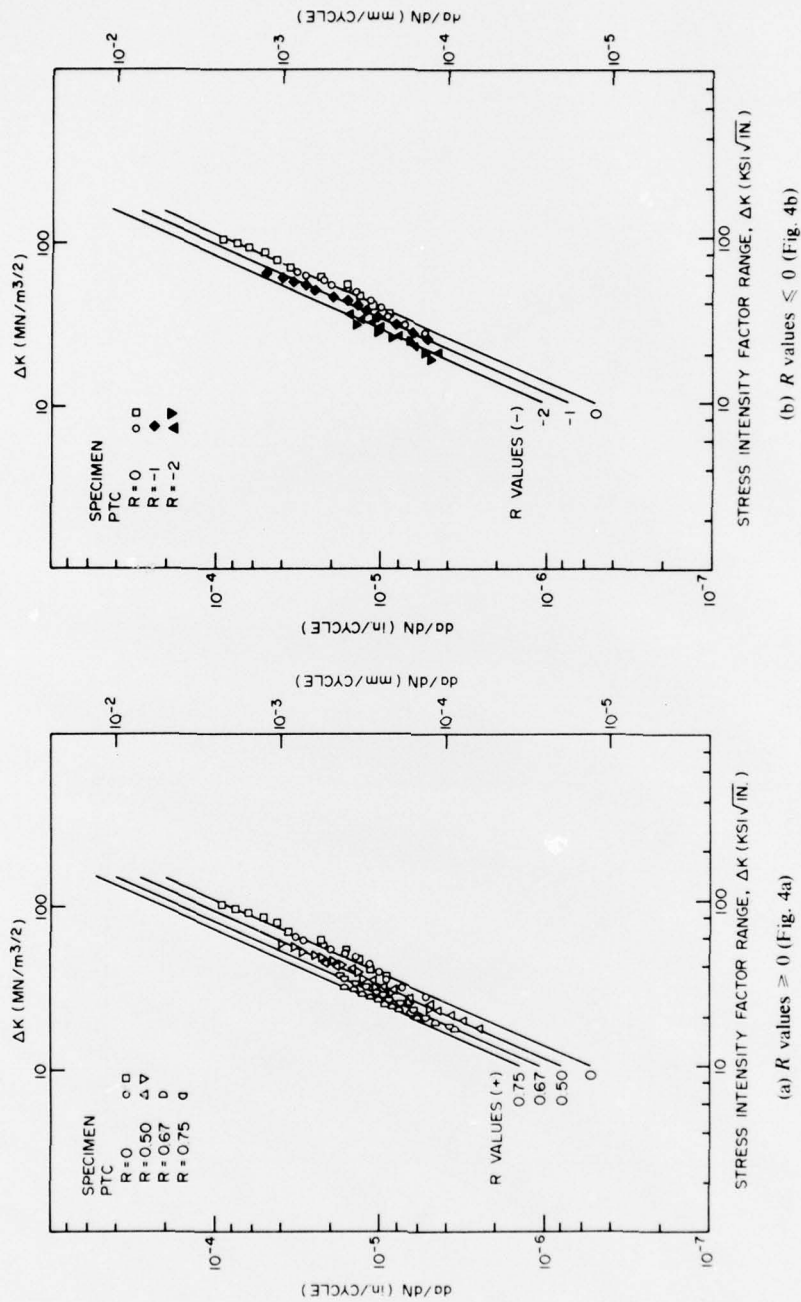
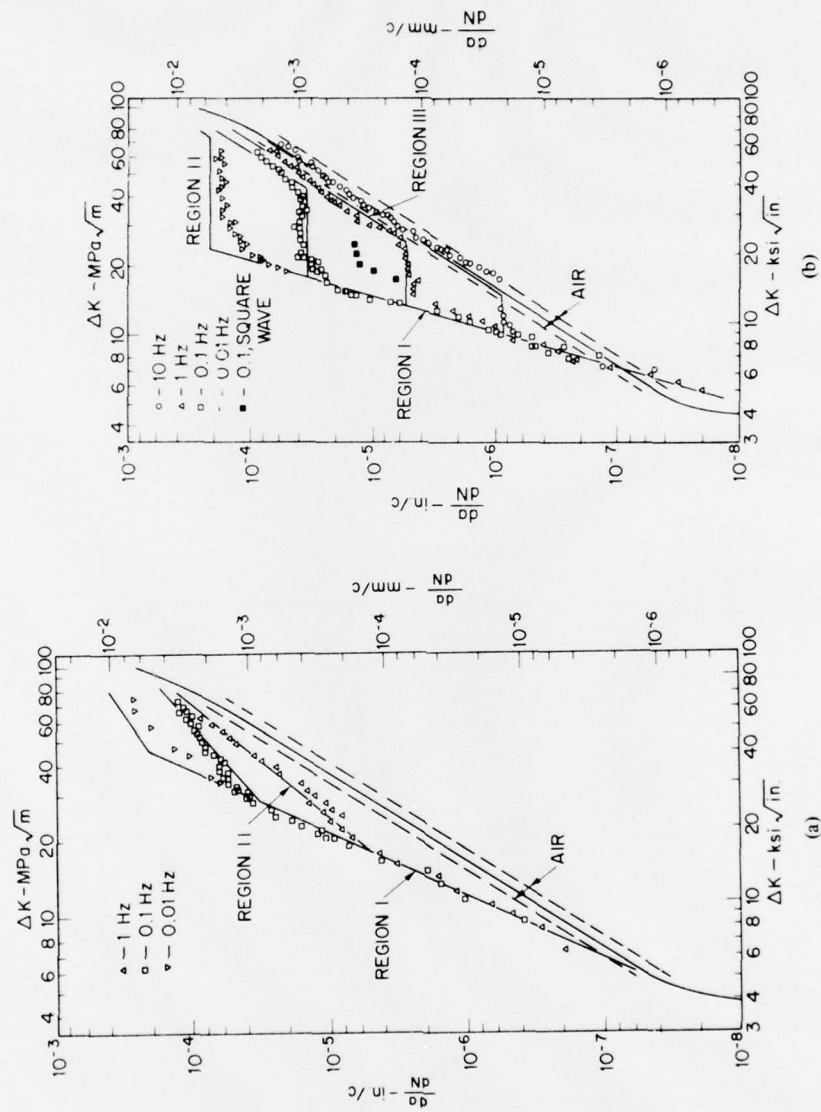Fig. 6 — Comparison of control (R = 0) data and that produced over a range of R values [22]:

7

Fig. 7 — da/dN vs ΔK for X-65 line pipe steel in air and salt water [21]: (a) freely corroding (Fig. 3); (b) cathodic potential (Fig. 2). (Reprinted from O. Vosikovsky, Trans. ASME, Ser. H, **97**, 298-304 (Oct. 1975). © 1975 American Society of Mechanical Engineers.)
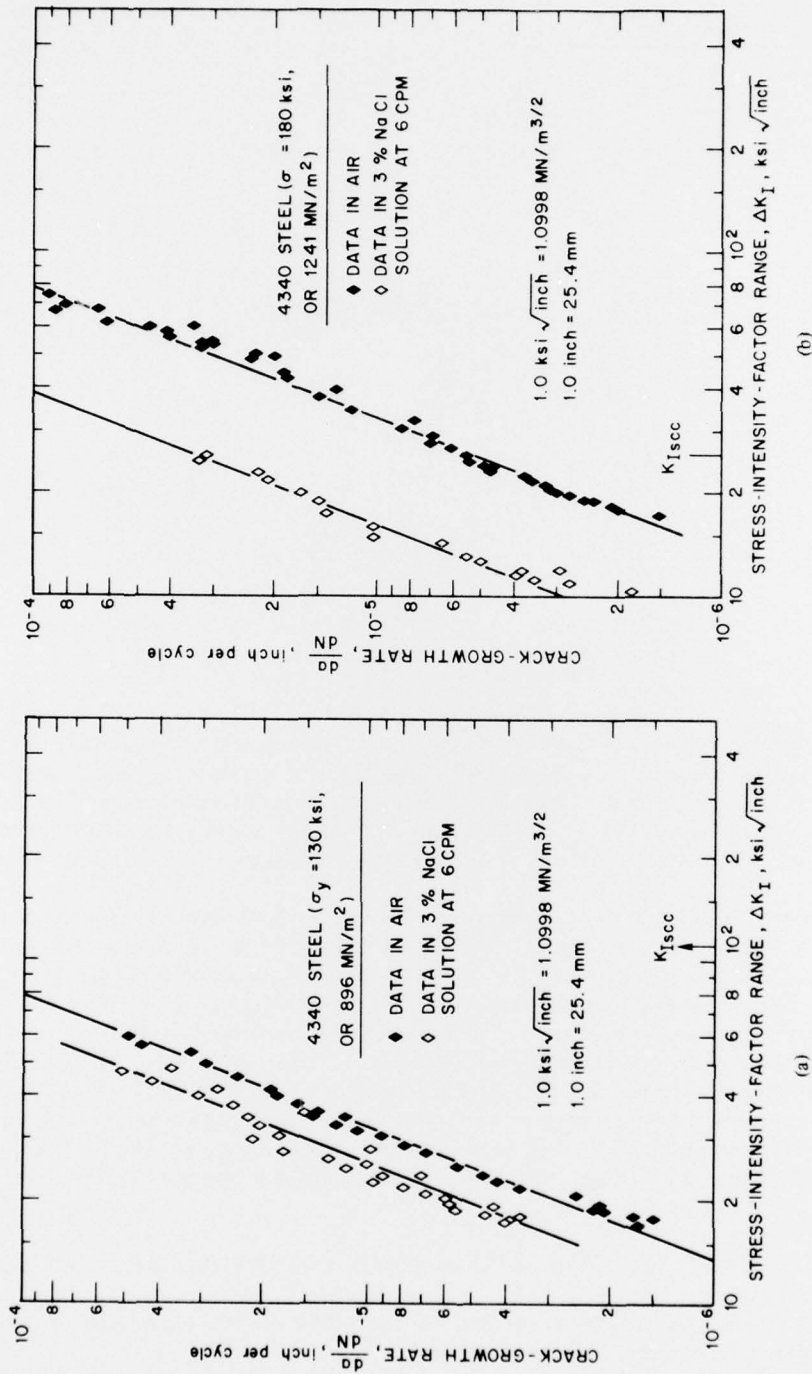
Fig. 8 — da/dN vs ΔK in air and NaCl solution for 4340 steel [19]: (a) $\sigma_{ys} = 130$ ksi (896 MPa) (Fig. 16); (b) $\sigma_{ys} = 180$ ksi (1240 MPa) (Fig. 17). (Reprinted, with permission, from Ref. 19, pp 202, 203. © 1973 American Society for Testing and Materials.)
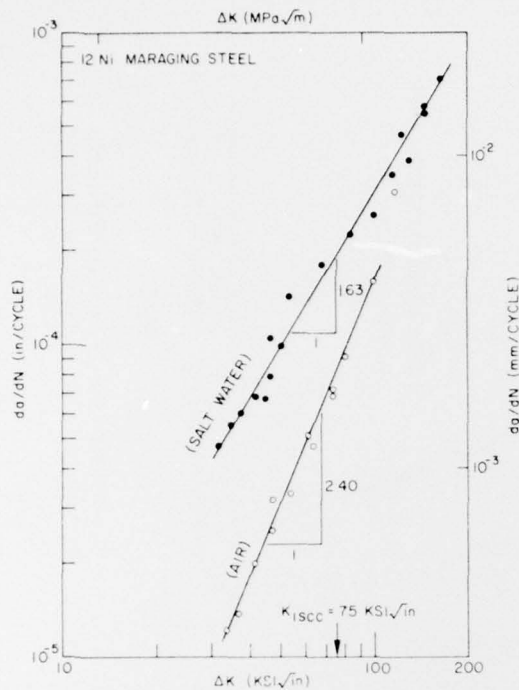
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Fig. 9 — da/dN vs ΔK in air and NaCl solution for 12Ni maraging steel (Ref. 39, Fig. 5)

Reexamination of Imhoff and Barsom's data on 12Ni maraging steel [2] suggests that Region II behavior was commencing at the uppermost limit of his data and went unrecognized. Paris [40] shows behavior similar to that of Crooker and Lange for a D6a steel. The most obvious conclusion here is that, except for Vosikovsky [21], the experimenters did not cover a wide enough range of da/dN values to charaterize completely the effects of corrosive environments.

Waveform — In adverse environments the waveform does have an effect, but its exact consequence appears unresolved. Barsom [20] found that the environmental effects occurred only during increasing tensile stresses. Crack-growth rates under sinusoidal, triangular, or positive sawtooth waveforms showed environmental effects, but under square or negative sawtooth waveforms they were the same as in air. This result was confirmed by Pelloux on 7075-T73 aluminum in a discussion to the same Ref. 20 and by Crooker, et al. [41]. Another discussion to Ref. 20, however, by Hudak and Wei, indicated that tests on 7075-T651 using both positive and negative sawtooth forms were identical. To further complicate matters with respect to waveform, Vosikovsky [21] finds that with cathodic potential, da/dN values from a square waveform, while lower than those using a triangular waveform, are still higher than those in air.

Stress Ratio — No references to studies on the effect of stress ratio have been found.

Amplitude — No references to studies on the effect of variable-amplitude loading on FCGR in aqueous environments have been found.

10

Service Conditions — Here, frequency and waveform as well as stress ratio and amplitude may well represent variables in service conditions.

CONDITIONS OF THE TEST-ENVIRONMENTAL

Composition of contaminate solution.
Solution flowing or still.
Cathodic protection — sacrificial anode or potentiostat.

Recent experimental work has shown that in a flowing solution the corrosion fatigue-crack-growth rate (CFCGR) was the same under both freely corroding and cathodically protected conditions. In a still solution CFCGR was accelerated in the cathodically protected specimen.

SOME CAUSES OF DISCREPANCIES AND MISINTERPRETATIONS

Limited *da/dN* Range

Schematic diagrams of various curves of *da/dN* vs ΔK postulated [42] for corrosion fatigue are seen in Fig. 10. Figure 11 depicts behavior exhibited by certain nonferrous alloys [43]. By referring back to Figs. 7, 8a, 8b, and 9 we see that the data apparently do not fit the postulated forms. Discussion of the data in Fig. 9 shows quite clearly that the range of data was not sufficient to characterize the environmental effect. The four orders of magnitude shown in Fig. 7 are more representative. The limited ranges studied have also led to divisions into regions, which differ from author to author. This must be clarified.

Material Thickness

This subject has already been covered in some detail. Clearly, to assess service conditions, the material must be tested in the processed form it will be used. Further, to elucidate the mechanisms of crack growth, reports of research must include processing information.
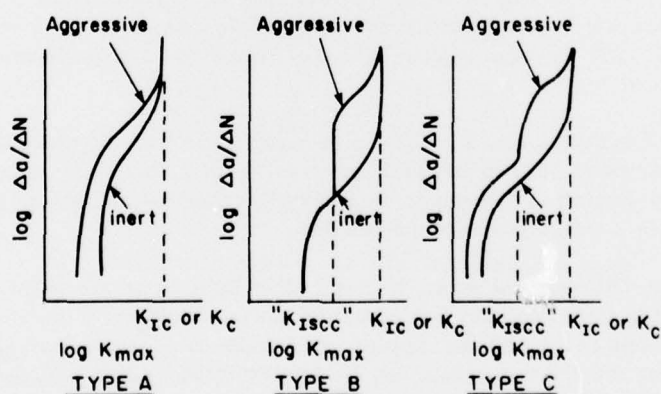

Fig. 10 — Types of corrosion fatigue crack-growth behavior. (Reprinted with permission, from Ref. 42, p. 387. © 1972 National Association of Corrosion Engineers.)
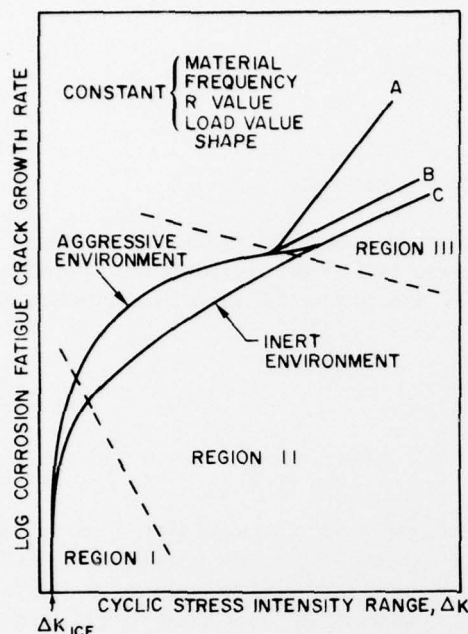
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Fig. 11 — Schematic of the influence of stress intensity on corrosion fatigue crack-growth rate. (Reprinted, with permission, from Ref. 43, p. 326. © 1972 National Association of Corrosion Engineers.)

VALUES OF EXPONENT n

The previous statement that specific values of n can be associated with specific types of steel microstructures is misleading. Not only are there indications that n may vary with tempering temperature and K_{Ic} (not yield strength), but also data show clearly that n is altered by an adverse environment. The dogmatic statement that $n \simeq 2$ for martensitic steels is belied by the data of Ref. 37. Here Miller also suggests that the highest values of n may reflect the effect of the atmospheric humidity, although no fractorgraphic evidence is presented. However, it has been shown in 17-4 stainless [2] that changes in fracture mode can be reflected by changes in n. When the fracture mechanism is by ductile striations, $n \simeq 2.26$; when microvoid coalescence (MVC) and cleavage appear, $n \simeq 4.0$. This mode change is seen in air tests with increased values of R.

Vosikovsky, however, notes an increase in n when the fracture mode changes from ductile striations in air ($n = 2.82$) to brittle striation in NaCl. This observation pertains only to high ΔK values in Region II. However, in Region I increases are also noted, since $n = 3.95$ (free corrosion) and $n = 6.20$ (cathodic potential).

Barsom's data [20] all show values of $n \approx 2.25$ in both air or salt water. For one material only, 12Ni maraging steel, electron fractographic analysis indicates a fracture mode of ductile striations for the tests in air and flat, fine-textured plateaus or quasi-cleavage in the salt solution. The fact that the salt-water data can be reinterpreted to give a slope greater than 2 is more compatible with the fracture appearance.

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CONCLUSIONS

1. More comprehensive and systematic characterization of materials is needed.

2. Increasing costs of material, machining, and labor handicap the research. Cooperation among laboratories with coordination by one would distribute the burden and increase the usefulness of the information.

3. To render such pooled information meaningful, a standardized test method is mandatory.

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